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Assessment of optical aberrations of tunable liquid crystal cylindrical microlenses

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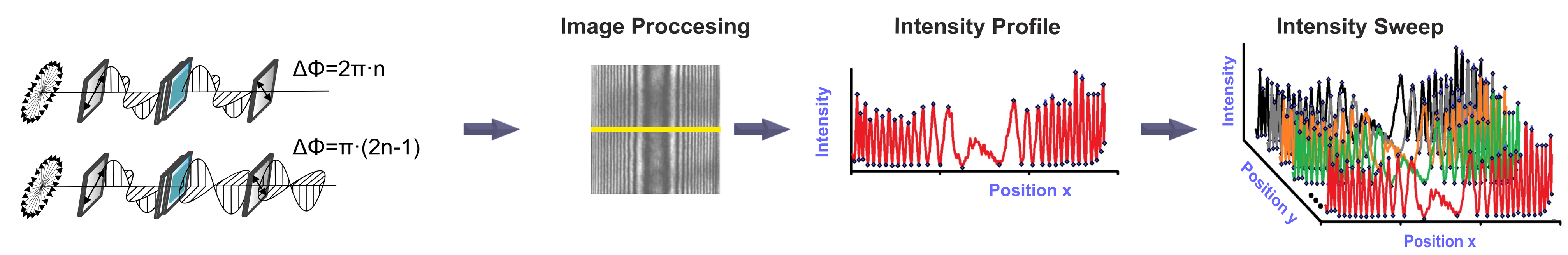
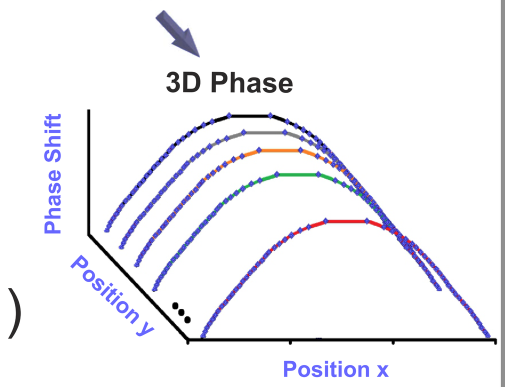
Abstract:

Cylindrical lenses can be used in some novel applications such as light-sheet microscopy, line illumination microscopy or autostereoscopic devices. However, as with any kind of lens, the main drawback is the generation of optical aberrations. These aberrations determine the image quality of the optical system.

In this work, optical aberrations in a liquid crystal (LC) cylindrical lens have been modeled and measured for the first time (to the best of our knowledge). We have developed our own application specifically to extract the 3D wavefront from an interference pattern. This software tool also allows us to obtain the optical aberrations based on Chebyshev polynomials. A tunable LC cylindrical lens has been designed and manufactured. Optical aberrations have been assessed by adjusting the control voltage applied to the device.

1. Software Design





1) Working principle:

The LC birefringence changes the polarization state of the incoming light. A Fringe Skeletonizing algorithm has been developed to detect the phase shifts.

2) Wavefronts:

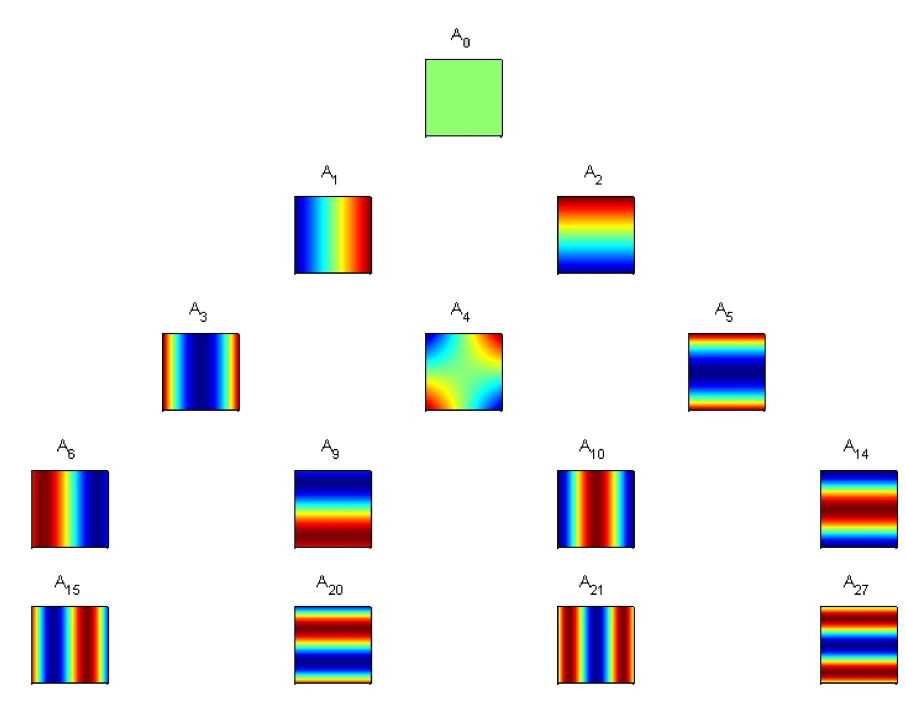
The Optical path length is obtained by Eq. 1

$$\Delta\Phi = \frac{2\pi}{\lambda}\cdot\int_{-r}^{r} n_{eff}(\theta)\,dz = \frac{2\pi}{\lambda}\Delta nd \quad (1)$$

3) Chebyshev Polynomials:

We computed the 2D coefficients (A_j) in Eq. 2 [1] using MATLAB code.

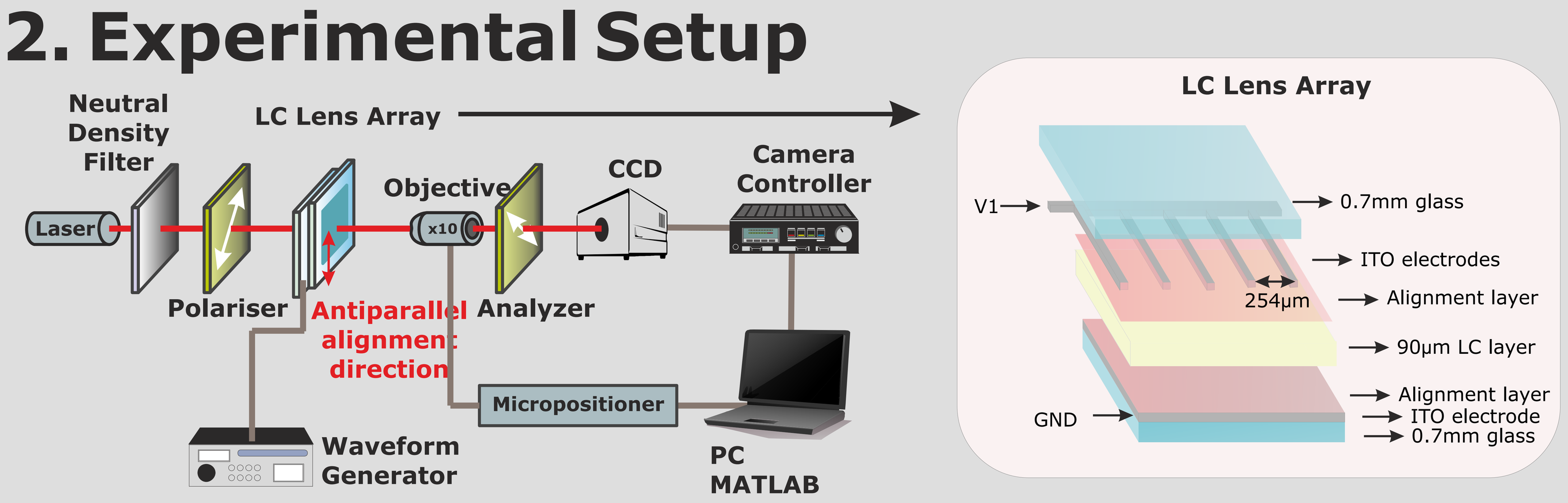
$$W(x,y) = \sum_j A_j F_j(x,y) \quad (2)$$



Order	Coefficient (Aj)	Un-normalized form (Fj)	Aberration
0	A_0	1	Piston
1	A_1	x	Tilt X
	A_2	y	Tilt Y
2	A_3	$2x^2-1$	X astigmatism
	A_4	xy	45º astigmatism
	A_5	$2y^2-1$	Y astigmatism
3	A_6	$4x^3-3x$	Primary coma X
	A_9	$4y^3-3y$	Primary coma Y
4	A_{10}	$8x^4-8x^2+1$	Primary spherical X
	A_{14}	$8y^4-8y^2+1$	Primary spherical Y
5	A_{15}	$16x^5-20x^3+5x$	Secondary coma X
	A_{20}	$16y^5-20y^3+5y$	Secondary coma Y
6	A_{21}	$32x^6-48x^4+18x^2-1$	Secondary spherical X
	A_{27}	$32y^6-48y^4+18y^2-1$	Secondary spherical Y

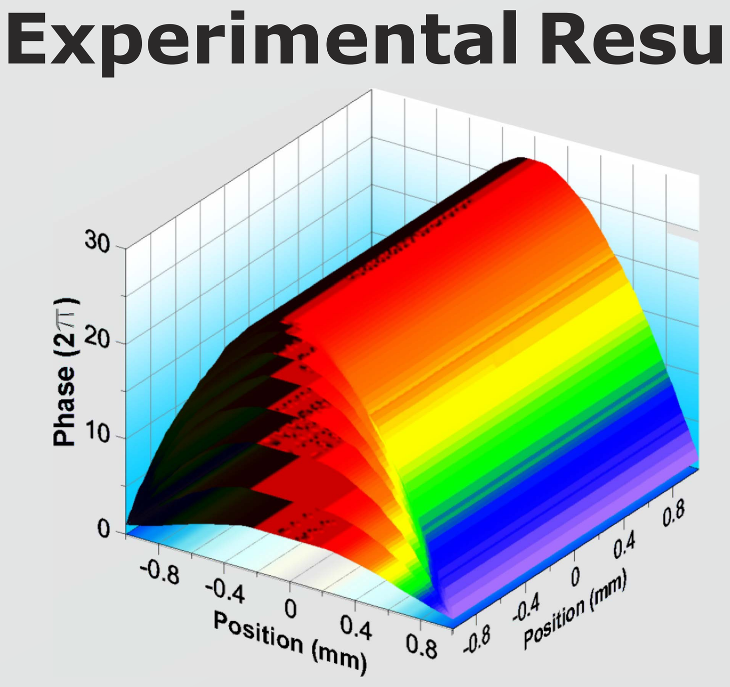
2D Chebyshev polynomials related to some classical aberrations [2].

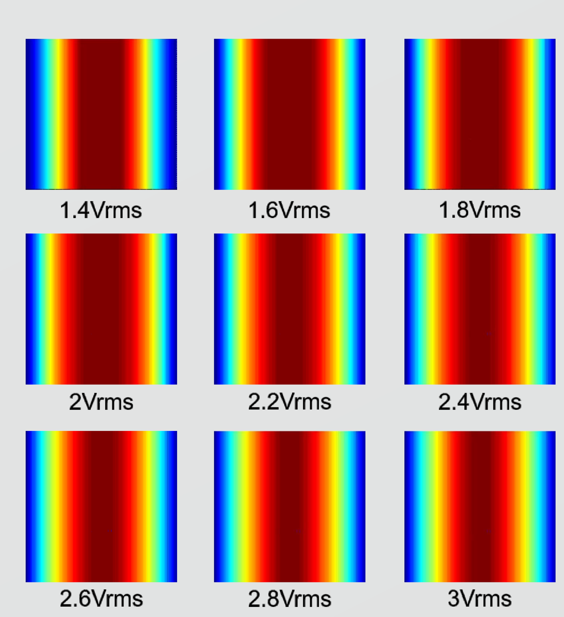
2. Experimental Setup



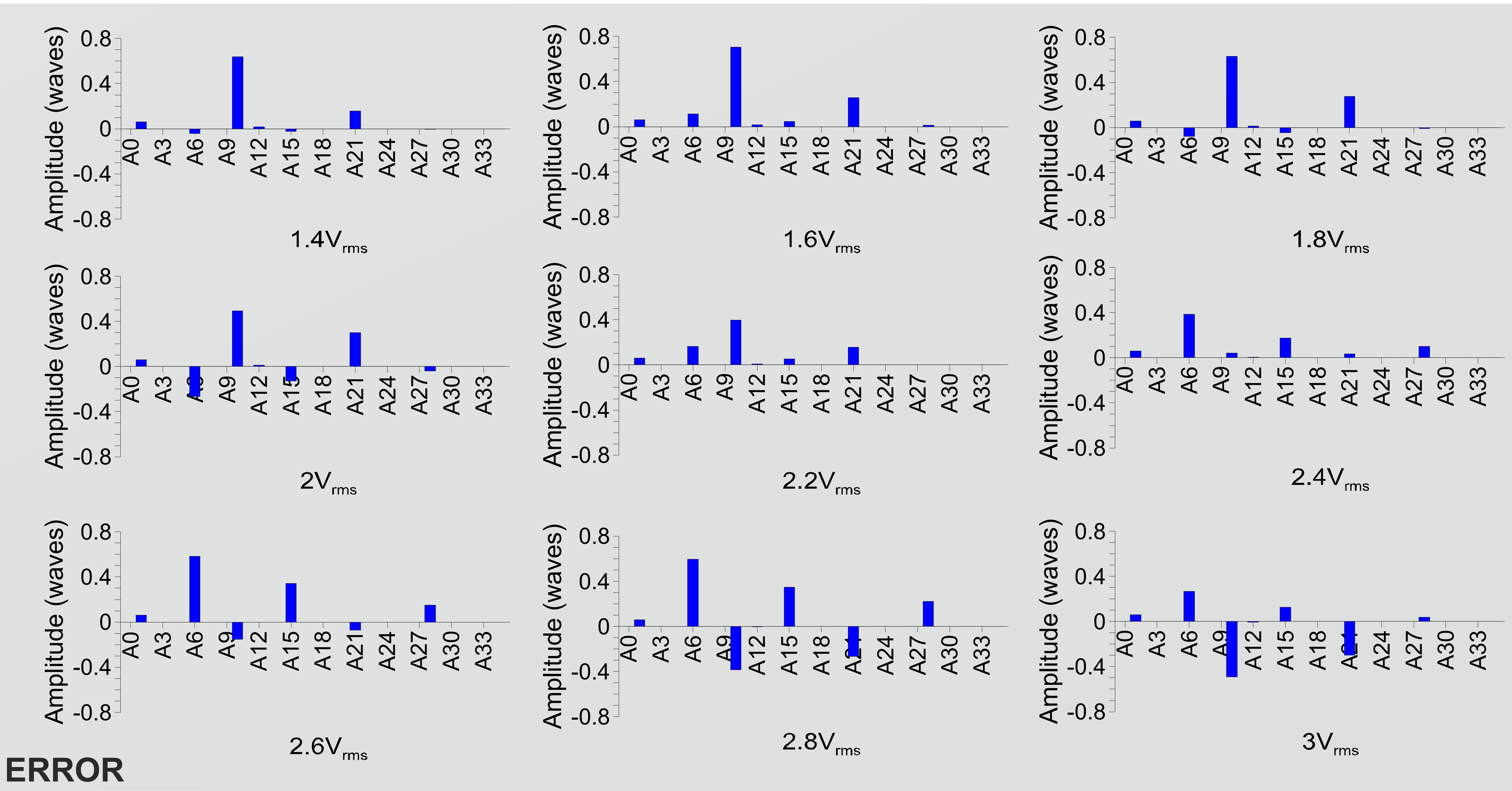
A proper phase profile, without defects such as shrinking of the LC lens aperture or plateau phase at the center of the LC lens, requires a specific ratio of thickness to diameter (d/t=2-3).

3. Experimental Results

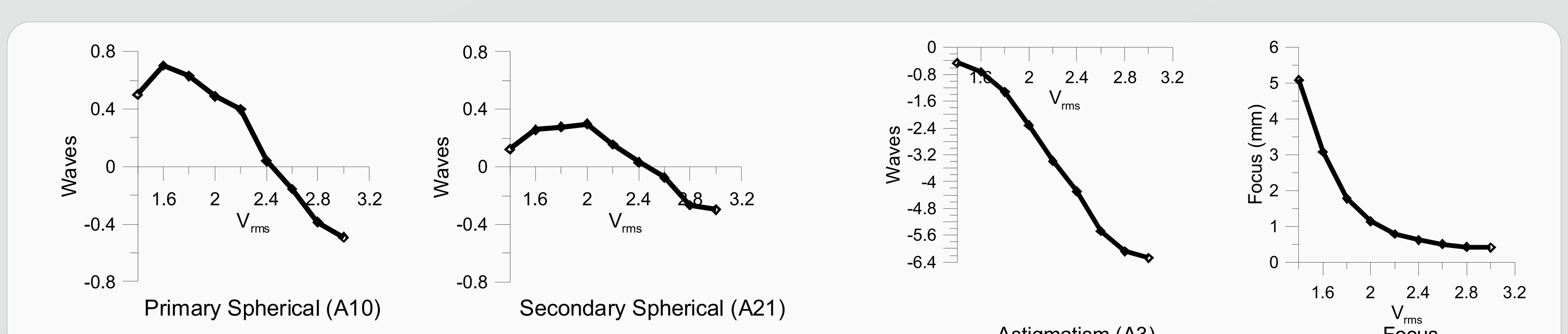




Eq. 2



- The phase maps shows a high phase tunability.
- There are no shrinking or plateau like defects as it was designed (d/t=2-3).



FIT ERROR

- Spherical aberration (A10) causes the rays of light to focus at different points resulting in a resolution loss and blurred images.
- In this lens, the spherical aberration can be positive or negative as a function of voltage so it can be considered as a spherical aberration compensation device.
- Spherical aberration can even be suppressed achieving an ideal lens for some specific voltages
- The astigmatism aberration (A3) is inversely proportional to the focal lenght of the cylindrical lens (Eq. 3).
- Eq. 4 has been used for a quantification of the quality of the fit.

$$f = \frac{\pi\cdot R^2}{\lambda\cdot\Delta\Phi} = \frac{\pi\cdot R^2}{\lambda\cdot K\cdot 2\pi\cdot|A_3|} \quad (3)$$

$$RMS_{FIT\,ERROR} = \sqrt{\frac{1}{N}\frac{1}{M}\sum_{i=1}^{N}\sum_{j=1}^{M}\left(W(i,j)-W'(i,j)\right)^2} \quad (4)$$

Conclusions:

- Optical aberrations have been modeled and measured in an LC cylindrical microlens for the first time.
- A specific algorithm developed by the authors has been used to extract the wavefronts and aberrations as a function of the applied voltage.
- A total control over the spherical and coma aberration has been demonstrated. The astigmatism aberration has been demonstrated to be inversely related to focal lenght.
- LC cylindrical lenses are sugested as aberration compensation devices.
- The aberrations can be reduced to minimum values, achieving a near ideal phase profile for some specific voltages.
- The fitting error has been measured, resulting in less than 0.0126λ with a maximum fluctuation of 0.006λ.

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Cylindrical lenses are promising devices for a wide range of applications [1-3]. This kind of lenses can be used in some novel applications such as light-sheet microscopy, line illumination microscopy or autostereoscopic devices. However, as any kind of lens, the main drawback is the generation of optical aberrations. These aberrations determine the image quality of an optical system. Interferometrists often like to represent wavefronts as Zernike polynomials. Zernike polynomials have been widely used because, unlike other polynomial set, they are orthogonal over a unit circle and represent balanced classical optical aberrations, yielding minimum variance over a circular pupil [4]. These characteristics are lost when non circular pupils are employed. Some research works have developed new coefficients for different pupils [5]. Notwithstanding that, they were targeted for rotational symmetric optics [6]. In the referred paper, 2D Chebyshev polynomials related to some Seidel aberrations are described. These ones form a useful orthogonal basis for optics of rectangular apertures, making them an attractive option for cylindrical lenses.

In this work, optical aberrations in a liquid crystal (LC) cylindrical lens have been modeled and measured, for the first time. We have developed our own application specifically to extract the 3D wavefront from an interference pattern. This software tool also allows us to obtain the optical aberrations based on Chebyshev polynomials. A tunable LC cylindrical lens has been designed and manufactured. Optical aberrations have been assessed by adjusting the control voltage applied to the device.

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